Overview of Energy Storage Technologies for Space Applications

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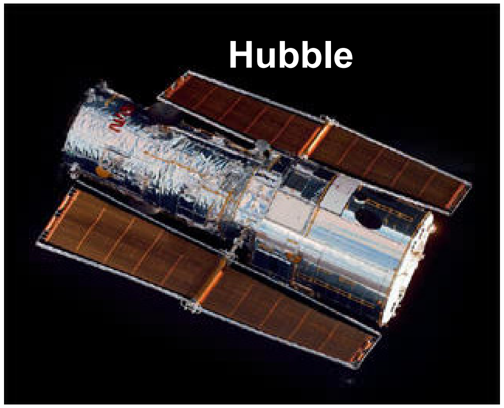
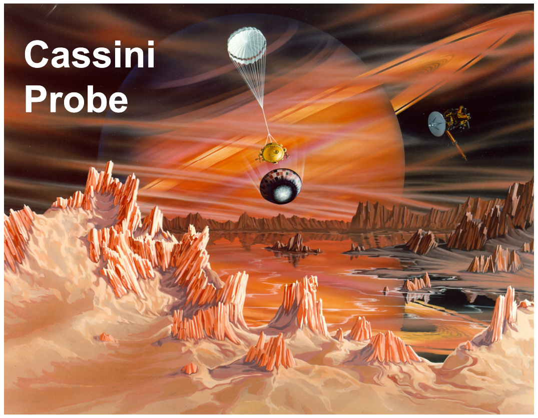
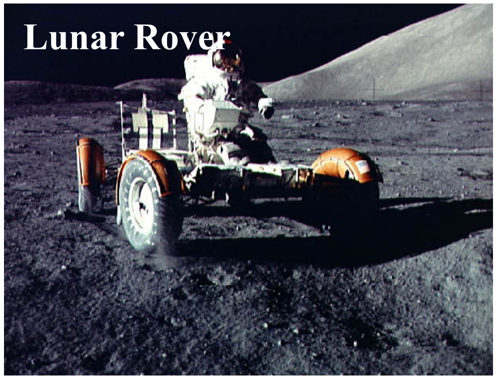
Outline

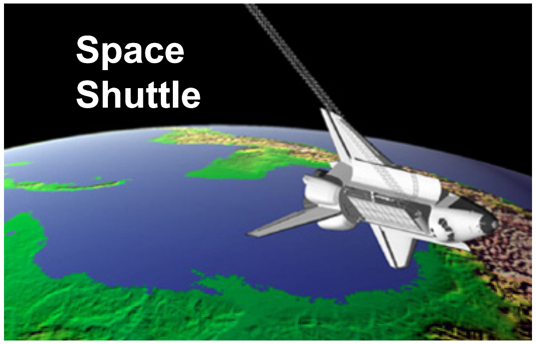
- Background
- Current State-of-Practice (SOP) Energy Storage Systems
- Future Space Missions and their Needs
- Advanced Energy Storage Systems Under Development
- Summary and Conclusions

Energy Storage Systems: Space Applications









Energy storage systems have been used in 99% of the robotic and human space missions launched since 1960

Space Applications of Energy Storage Devices

- Energy storage are used space missions to:
  - Provide **primary electrical power** to launch vehicles,crew exploration vehicles, planetary probes, astronaut equipment
  - **Store electrical energy in solar powered orbital and Surface missions** and provide electrical energy during eclipse periods
  - **Meet peak power demands** in in nuclear powered rovers, landers and planetary orbiters

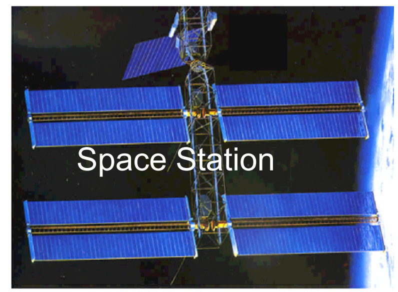
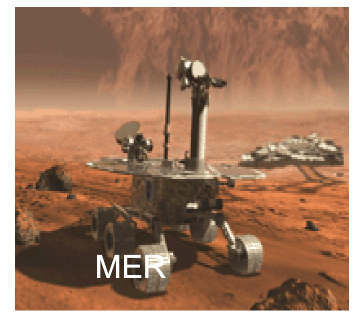
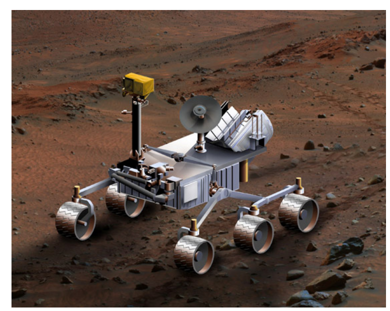
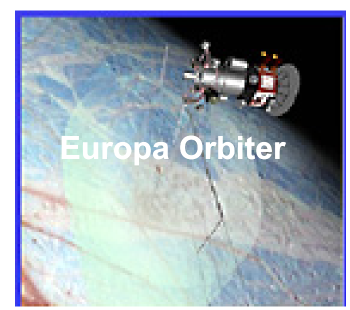


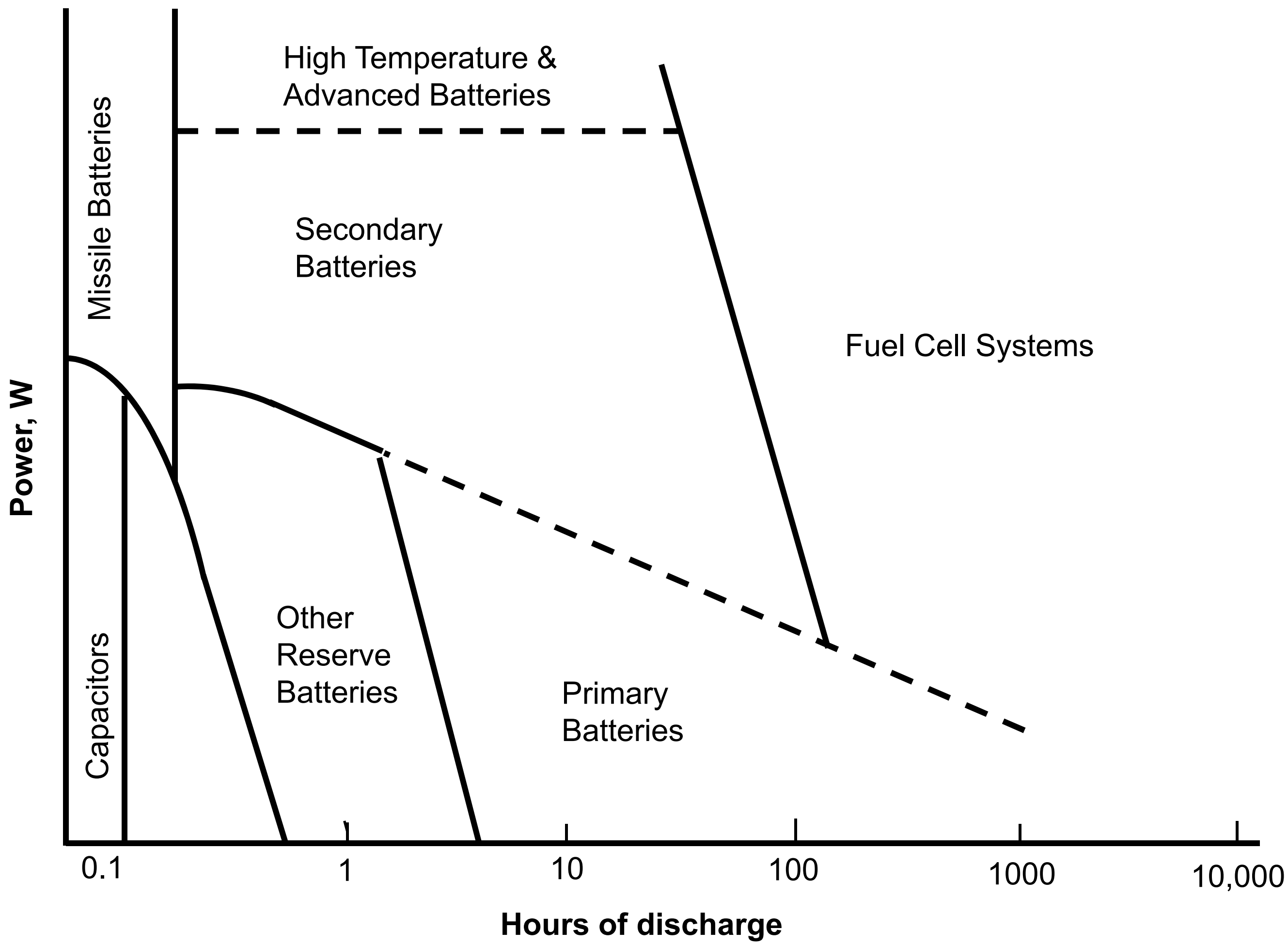
Figure 3-8: Space Station Solar Array







Performance Envelope of Electrochemical Power Sources



Service life dictates the choice of energy storage technology

Energy Storage Systems: Applications

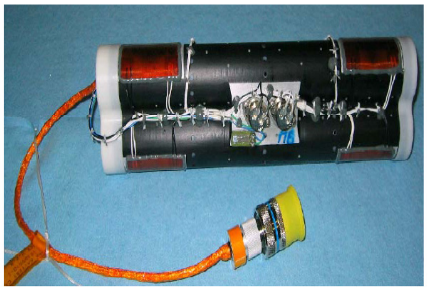
System	Application
Capacitors – Double-layer, ultra super	RPS Powered Missions.
Primary Batteries – Ag-Zn, Li-SO_2, Li-$SOCl_2$	Launch vehicles, probes, and astronaut equipment.
Rechargeable Batteries – Ni-Cd, Ni-H_2, Li-Lion	Earth / Mars Orbital Missions; Outer / Inner Planetary Orbiters; Surface Missions; Astronaut Equipment

System	Application
Fuel Cells – Alkaline, PEM	Surface Missions; Shuttle / CEV
Regenerative Fuel Cells – Alkaline, PEM	Lunar Habitat; Mars Habitat
Flywheels – Energy only; Energy and momentum	Earth Orbital Missions (GEO & LEO);

State-of-the-Practice Energy Storage Devices

SOP Space Batteries

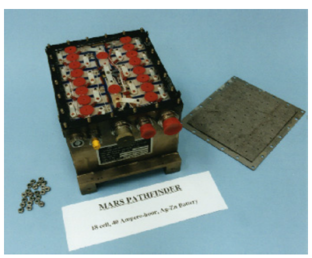
Primary Batteries



Li-SO_2 Mars
Exploration Rover
(MER) Battery

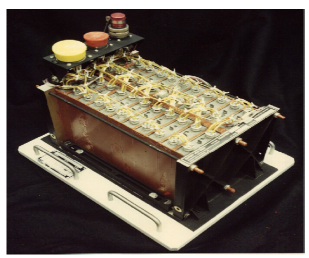
Li-$SOCl_2$
Pathfinder
Lander Battery

Rechargeable Batteries

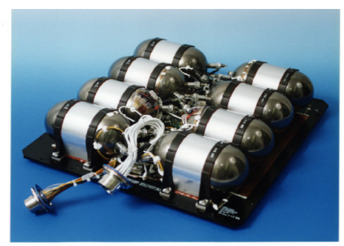


Ag-Zn Battery

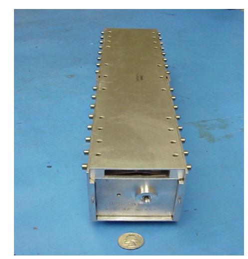
Mars Pathfinder
Lander



Standard Ni-Cd
Solar Max
Battery

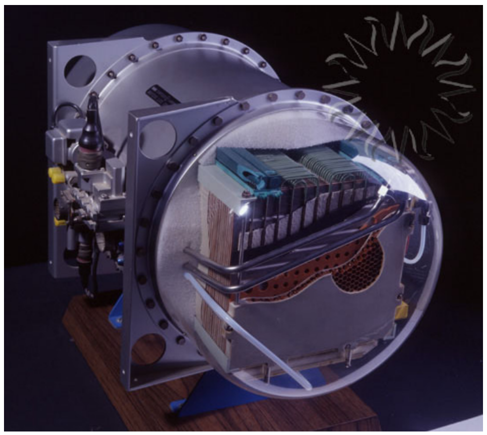


CPV
Ni-H_2Battery
Odyssey 2



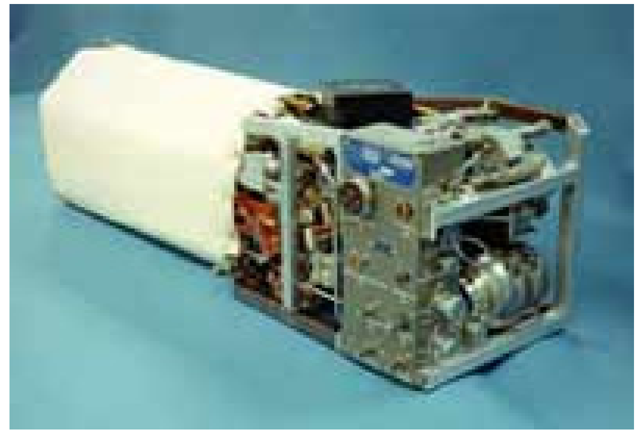
Li-Ion
Battery
MER Rover

SOP Fuel Cells



Polymer Electrolyte Membrane
(PEM) Fuel Cell
(Gemini)

Alkaline Fuel Cell
(Apollo)

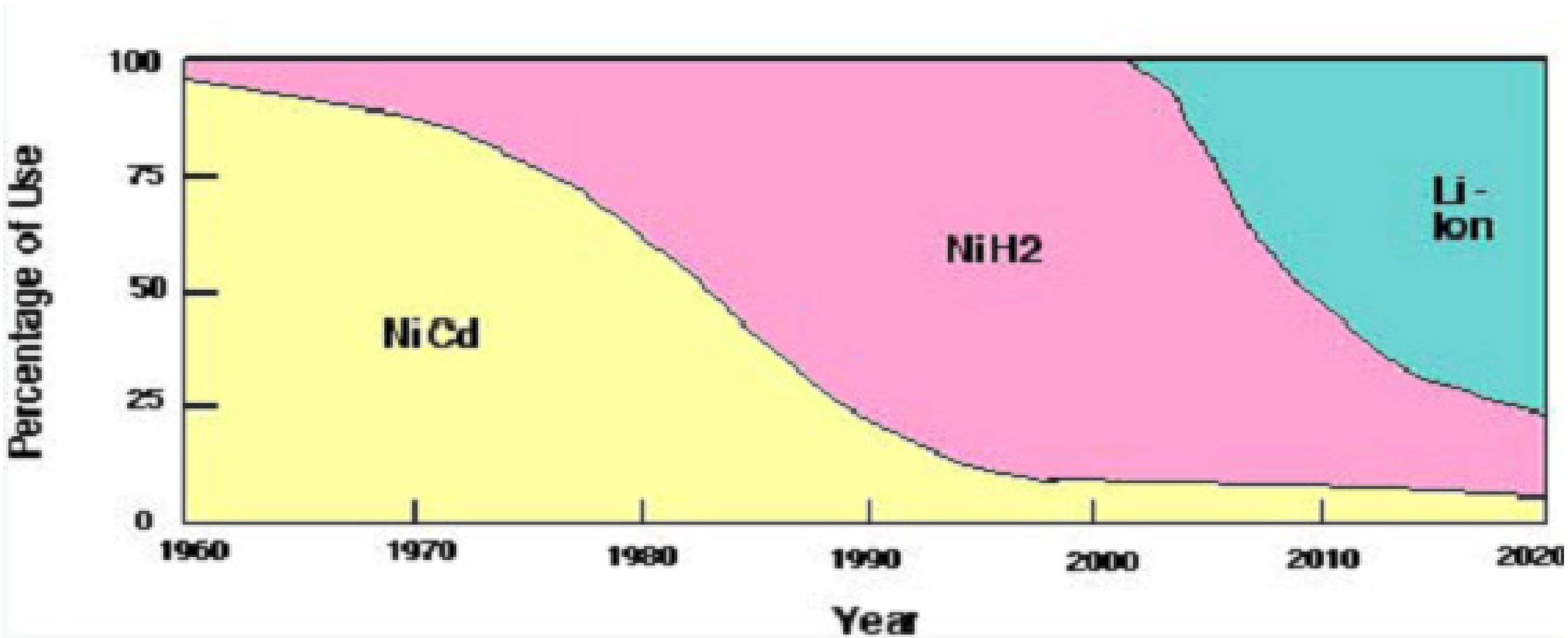


Alkaline Fuel Cell
(Space Shuttle)

Energy Storage Systems: Current State-of-Practice

System	Technology	Mission	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Cycle Life	Mission Life (yrs)	Issues
Primary Batteries	Ag-Zn Li-SO_2, Li-$SOCl_2$	Delta Launch Vehicles Cassini Probe MER Lander Sojourner Rover	90-250	130-500	-20 to 60	1	1-9	• Limited operating temp range • Voltage delay
Rechargeable Batteries	Ni-Cd, Ni-H_2	TOPEX HST Space Station	24-35	10-80	-5 to 30	> 50,000 @25%DOD	>10	•Heavy and bulky • Limited operating temp range
Adv. Rech. Batteries	Li-Ion	Spirit & Opportunity Rovers	90	250	-20-30	> 400 @ 50% DOD	>2	Cycle Life
			Power Rating (kW)	**Specific Power (W/kg)**	**Power Density (W/l)**	**Efficiency %**	**Maintenance Frequency (hrs)**	
Fuel Cells	Alkaline H_2-O_2	Apollo, Shuttle	10	90	155	70%	2600	Heavy and Bulky Limited to short missions

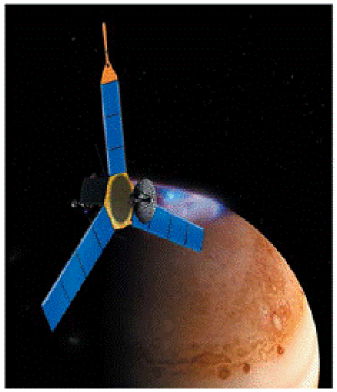
The Evolution Of Rechargeable Battery Technology



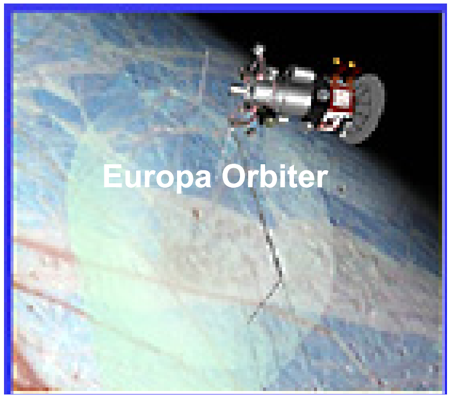
- Energy storage technologies take 10-15 years for development and infusion into missions.
- We are at the threshold of implementing Li-ion for space missions.

Future Space Missions and their Needs

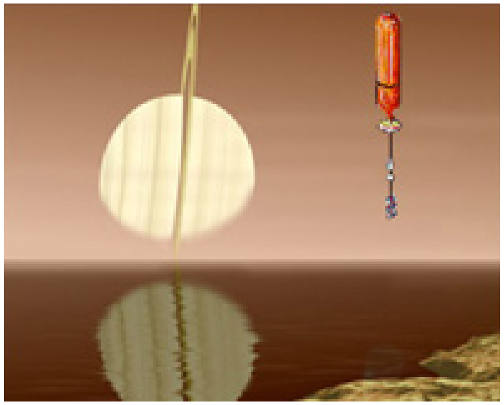
Solar System Exploration Mission Concepts- Far Term



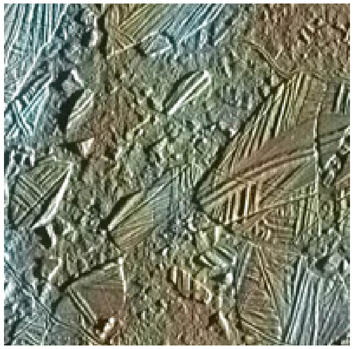
JUNO
(2010-2015)



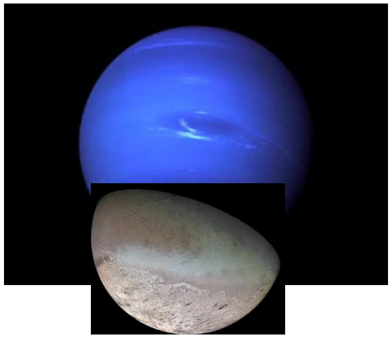
Europa Orbitter
(2015-2020)



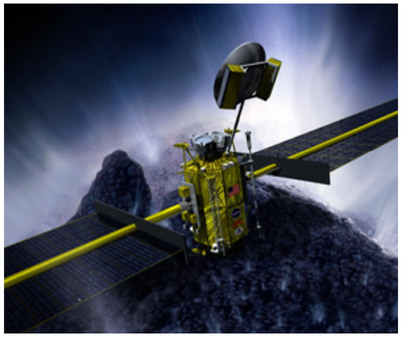
Titan Organic Explorer
(2015-2020)



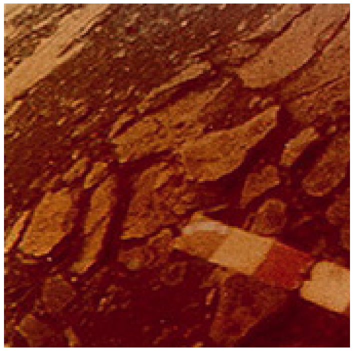
Europa Surface
and Subsurface
(>2020)



Neptune/Triton Orbiter (>2020)

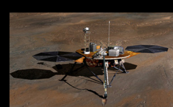
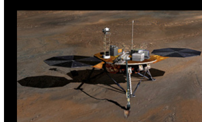
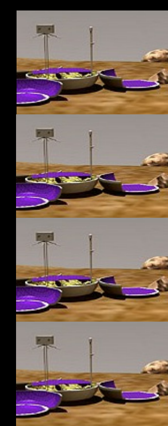
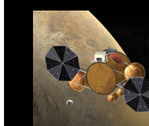


Comet Nucleus
Sample Return
(>2020)



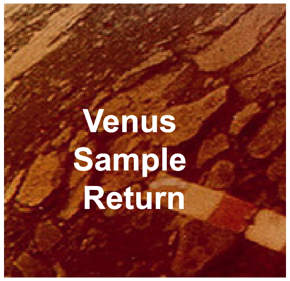
Venus Sample Return
(> 2020)

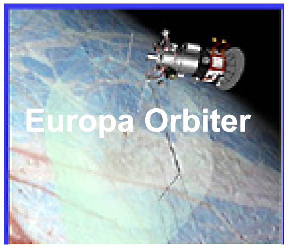
Mars Exploration Architecture
2009 - 2024

2009	2011/2013	2016	2018	2020	2022	2024
MSL 	**Scout or Mars Science Orbiter with telecom**   **OR**  	**Mid Rovers or AFL**   **OR** 	**Scout**  LSAM	**Planetary evolution and meteorology network** 	**MSR orbiter and return capsule** 	**MSR mobile** 

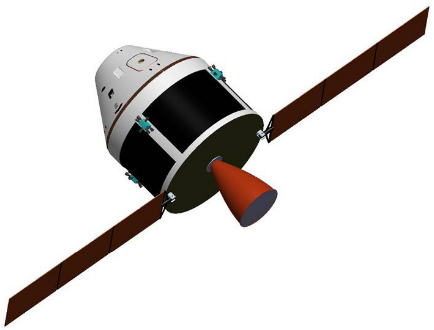
Summary of Energy Storage Technology Needs of NASA Planetary Science /Solar System Exploration Missions

1. **Low temperature batteries (**primary(<-100°C) and rechargeable (<-60°C) batteries) for planetary probes and Mars surface missions
2. **High temperature batteries** (> 475 °C) for inner planetary missions
3. **Long calendar life** (>15 years), high specific energy (>120 Wh/kg) & radiation tolerant rechargeable batteries for outer planetary missions
4. **High specific energy** (>120 Wh/kg) and Long cycle life (>30,000 cycles) rechargeable batteries for Mars and earth orbital SEC, SEU & origins missions
5. **High specific energy** primary batteries (>500 Wh/kg) for planetary probes



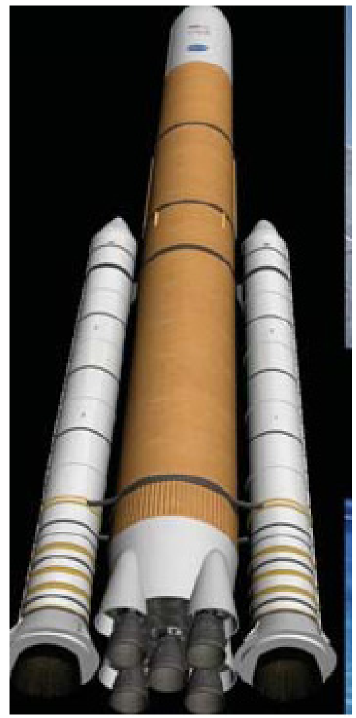


Exploration Missions (2010-2030)

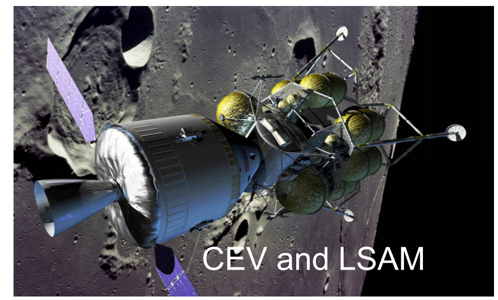


Crew Exploration Vehicle (CEV)

Crew Launch Vehicle (CLV)

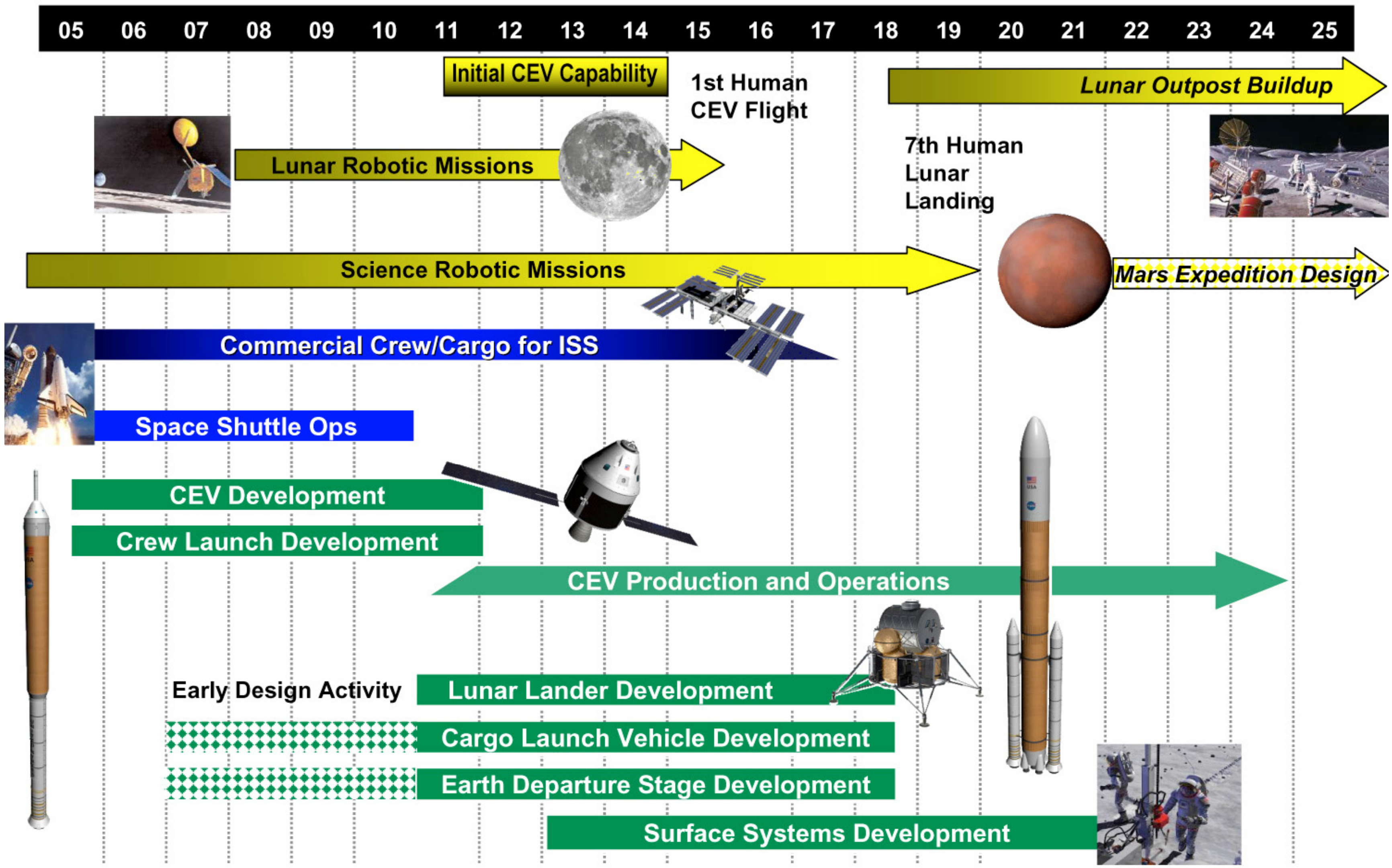


Cargo Launch Vehicle (CaLV)



The role of the Exploration Systems Mission Directorate (ESMD) is to develop a constellation of new capabilities and supporting technologies that enables sustained and affordable human and robotic exploration of the Moon, Mars, and beyond.

NASA's Exploration Roadmap

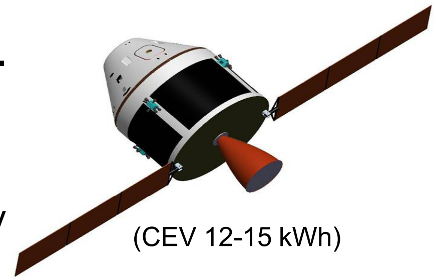


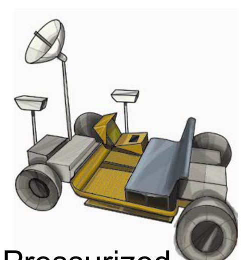
Summary of Energy Storage Technology Needs of Future Exploration Missions

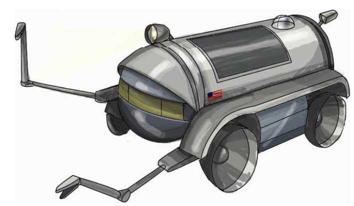
1. **Safe, High Specific Energy and Long Life Rechargeable Li-Ion Batteries** (32V, 1-15 kWh) are required for Crew Exploration Vehicle (CEV), Crew Launch Vehicle (CLV) , Heavy Lift Launch Vehicle (HLLV), Lunar Surface Ascent Module (LSAM), Astronaut Extravehicular Activity (EVA) Suit, Surface systems etc.,

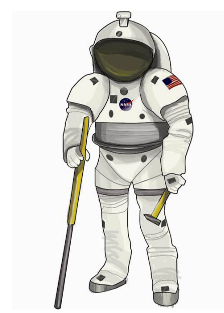
2. **High specific Power Safe, and Lonf Life Polymer Electrolyte Membrane and Regenerative Fuel Cells** are required for a wide range of surface elements, including advanced EVA, pressurized and unpressurized rovers, and for large surface power plants as part of a PV/RFC power system.

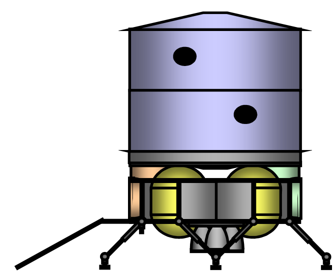
- 1KW max class for Advanced EVA PLSS,
- 2-8 KW class for un-pressurized rovers
- 25KW class for photovoltaic (PV) / regenerative fuel cell (RFC) power plant and pressurized rover applications.


(CEV 12-15 kWh)


Un Pressurized Rover 2-4 kW


Lunar Pressurized Rover 15-25 kW


EVA (0.2-1.0 kW)


Lunar Habitat (15-25 kW)

Advanced Energy Storage Systems Under Development

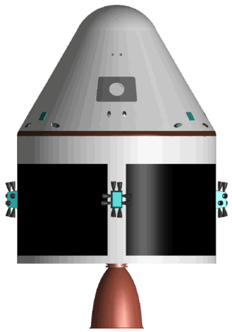
Space-Rated Li-Ion Batteries

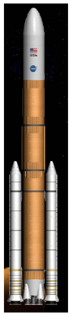
- Product
  - Develop space-rated high specific Energy Li-ion batteries for future human and robotic exploration missions
    - 200Wh/kh (Cell)
    - 160 Wh/kg (Battery)
    - 300 Wh/l (Battery)
    - > 30 K cycles (30%DOD)
    - -60 to + 60 C Operation

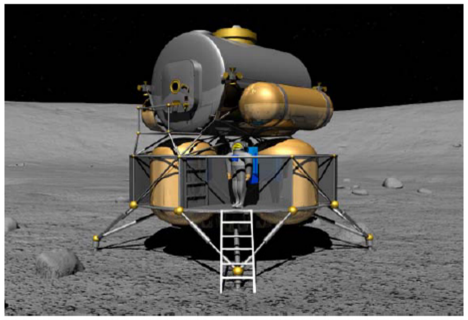
- Schedule
  - 2006-2010

- Sponsor
  - NASA-ESMD

- Team:
  - NASA-GRC(lead(, NASA-JSC, NASA-JPL, NASA-MSFC)
  - UT Austin, Caltech, USC and Industry:

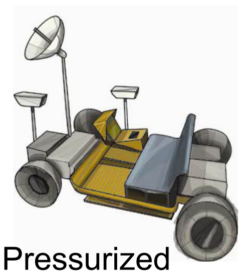




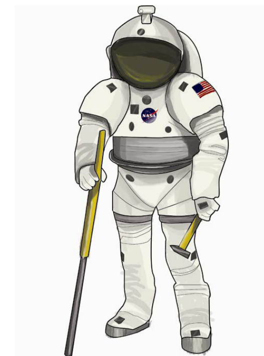


PEM Fuel Cells

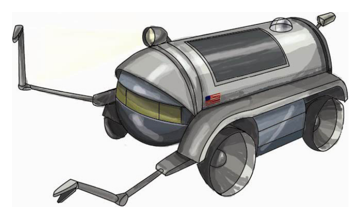
- Product
  - Develop PEM primary and regenerative fuel cells for future human lunar exploration missions
    - 1-kW max class for advanced EVA portable life support systems (primary fuel cell)
    - 8-kW class for un-pressurized rovers (primary fuel cell)
    - 25-kW class for RFC surface power plants and pressurized rovers (Regenerative Fuel Cell).
- Schedule
  - 2006-2010
- Sponsor
  - NASA-ESMD
- Team:
  - NASA-GRC (lead), NASA-JSC, NASA-JPL,
  - UT Austin, Caltech, USC and Industry:



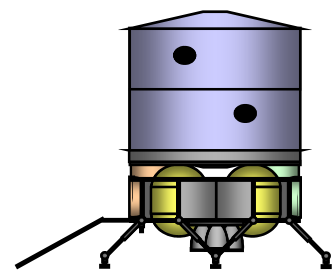
Un Pressurized Rover 2-4 kW



EVA (0.2-1.0 kW)



Lunar Pressurized Rover 15-25 kW



Lunar Habitat (15-25 kW)

Summary and Conclusions

- Energy storage systems have been used in 99% of the robotic and human space missions launched since 1960
  - Launch Vehicles: Ag-Zn batteries
  - GEO, LEO Spacecraft: Ni-Cd, Ni-H2
  - Space Shuttle: Alkaline Fuel Cells
- Future space missions have unique energy storage requirements
  - Large energy storage Capability (`MWH)
  - Mass and volume efficiency (2-10 X Vs SOP)
  - Long life (> 15 years)
  - Ability to operate in extreme environments
- State of practice primary and rechargeable batteries have limited performance capabilities and do not meet many of the above mentioned needs.
  - Limited life (5-10 years)
  - Limited operating temperature range (-20o-60oC for rechargeable, -40o – 60oC)
  - Radiation tolerance poorly understood
  - Heavy and bulky (30 Wh/kg for rechargeable)
- Development of advanced energy storage technologies required to meet future space mission needs
  - Fuel Cells: Medium power PEM Fuel Cells, Regenerative fuel cells, Small fuel cells
  - Primary Batteries: High specific energy, RAD hard Low temperature batteries
  - Rechargeable Batteries: High Specific energy, Long Life, RAD Hard, Low Temp. Batteries
  - Fly wheels

Acknowledgements

The work presented here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Backup slides

Characteristics of SOP Primary Batteries

Type	Application	Mission	Specific Energy, Wh/kg (b)	Energy Density, Wh/l (b)	Operating Temp. Range, °C	Mission Life (yrs)	Issues
$Li-SO_2$	Cell		238	375	-40 to 70	<10	Voltage Delay
	Battery	Galileo Probe Genesis SRC MER Lander Stardust SRC	90-150	130-180	-20 to 60	9	
$Li-SOCl_2$	Cell		390	878	-30 to- 60	>5	Severe voltage delay
	Battery	Sojourner Deep Impact DS-2 Centaur Launch batteries	200-250	380-500	-20 to 30	< 5	
$Li-CF_x$	Cell		614	1051	-20 to 60		Poor power capability

Limitations

- Moderate specific energy (100-250 Wh/kg)
- Limited operating temp range (-40 C to 70^{o}C)
- Radiation tolerance poorly understood
- Voltage delay

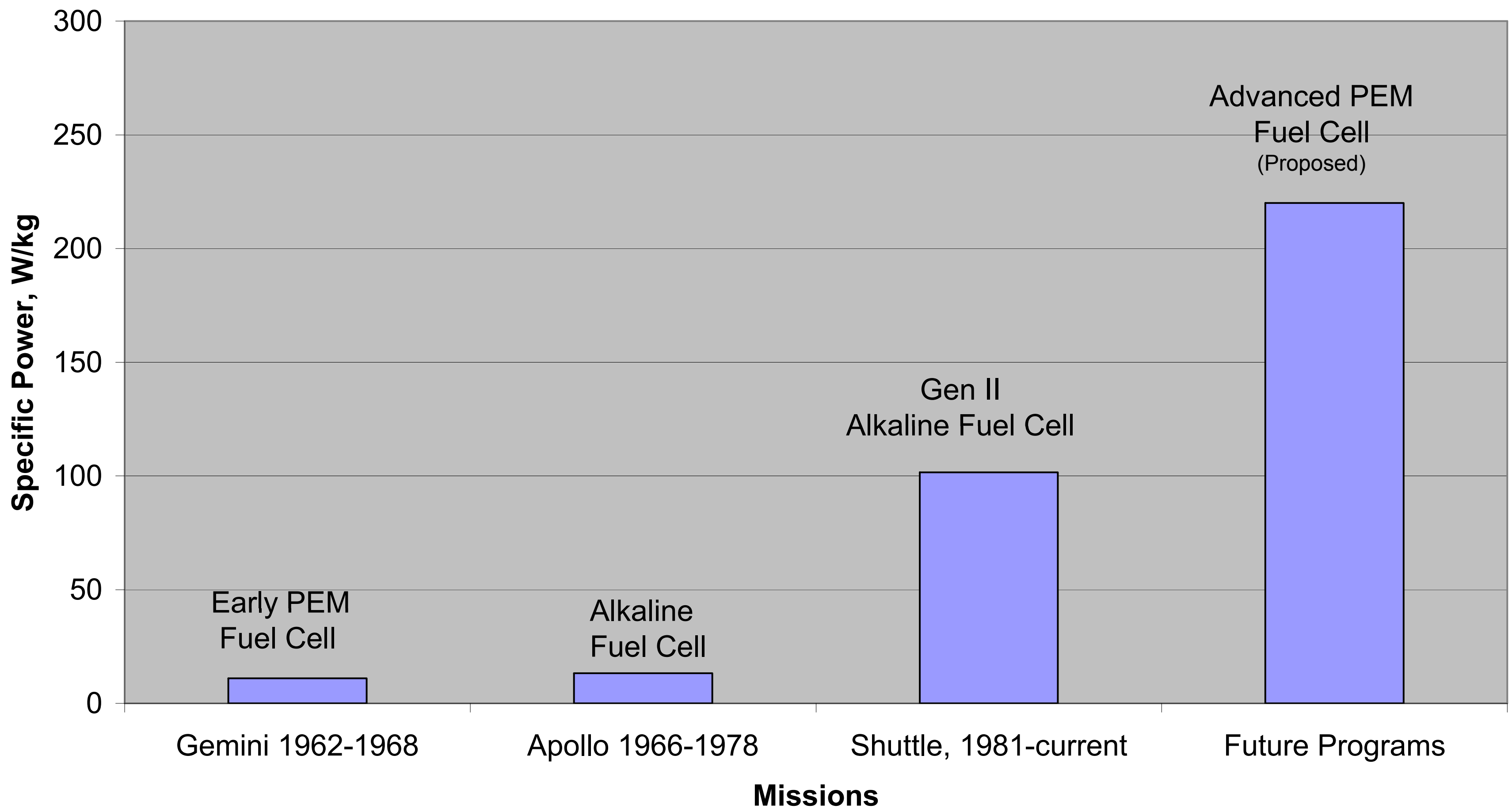
Characteristics SOP Rechargeable Batteries

Technology	Mission	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Design life, Years	Cycle life	Issues
Ag-Zn	Pathfinder Lander	100	191	-20 t0 25	2	100	Electrolyte Leakage Limited Life
Ni-Cd	Landsat, TOPEX	34	53	-10 to 25	3	25-40K	Heavy Poor Low Temp. Perf.
Super Ni-Cd	Sampex Battery, Image	28-33	70	-10 to 30	5	58K	Heavy Poor Low Temp. Perf
IPV $Ni-H_2$	Space Station, HST, Landsat 7	8-24	10	-10 to 30	6.5	>60K	Heavy, Bulky Poor Low Temp. Perf
CPV $Ni-H_2$	Odyssey, Mars 98 MGS, EOS Terra Stardust, MRO	30-35	20-40	-5 to 10	10 to 14	50 K	Heavy, Bulky Poor Low Temp. Perf
SPV $Ni-H_2$	Clementine, Iridium	53-54	70-78	-10 to 30	10	<30 K	Heavy Poor Low Temp. Perf
Li-Ion	MER-Rover	90	250	-20to 30	1	>500	Limited Life

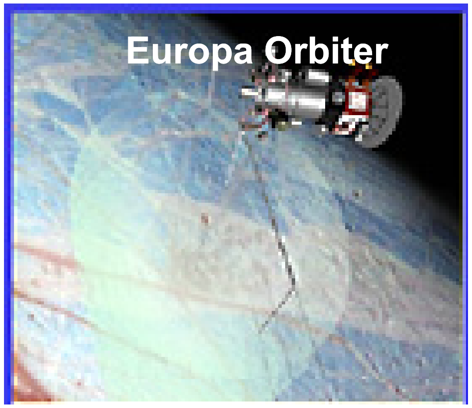
Limitations of Ni-Cd & Ni-H2 batteries:

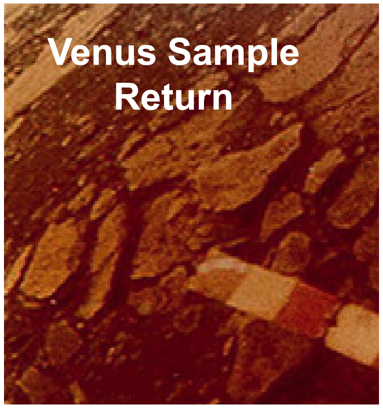
- Heavy and bulky
- Limited operating temp range (-10°C to 30°C)
- Radiation tolerance poorly understood.

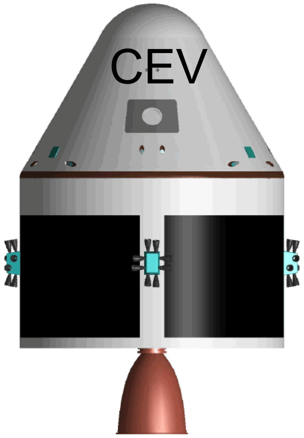
Characteristics of Space Fuel cells

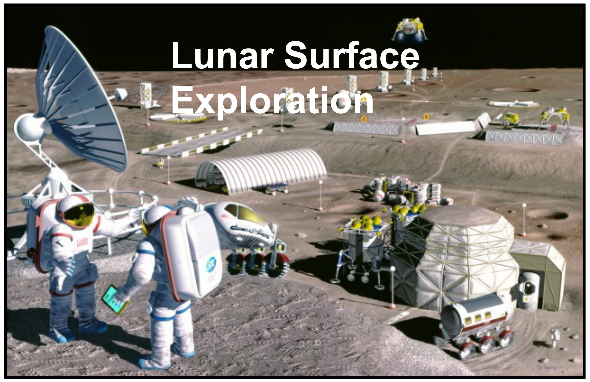


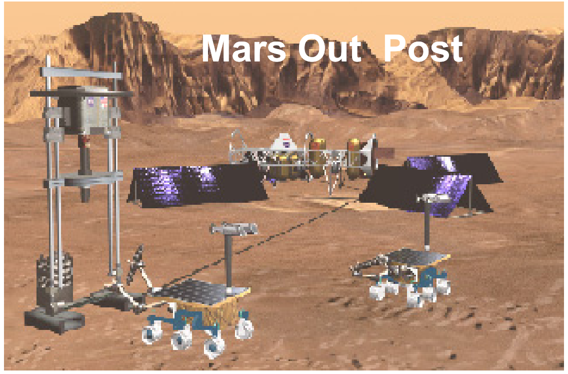
Energy Storage Systems: Future Space Applications











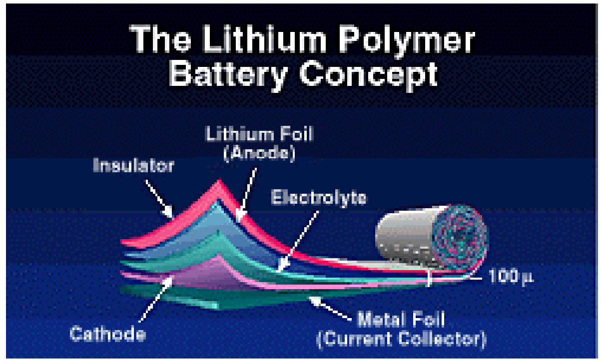
Future human and robotic exploration missions require advanced energy storage systems.

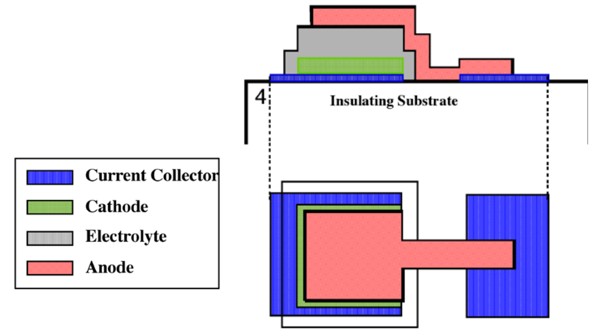
- **Critical capability requirements include: mass and volume efficiency (2-10 X Vs SOP), long life, safety, and the ability to operate in extreme environments.**

Summary

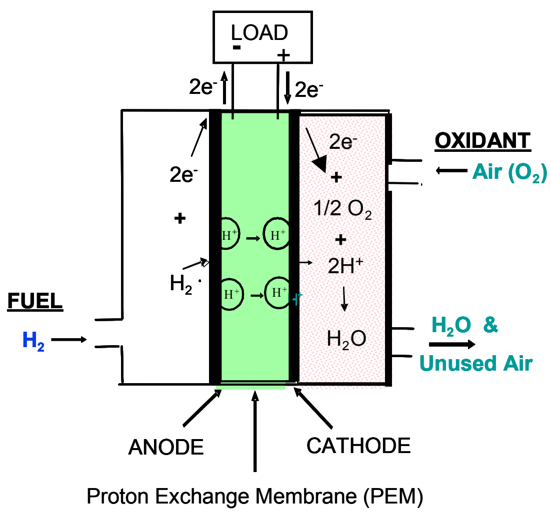
- NASA is planning a number of exciting robotic and human space exploration missions for the exploration of space
  - Robotic Lunar Exploration Missions (>2008)
  - Mars Science Laboratory (2009)
  - Crew Exploration Vehicle (> 2010)
  - Jupiter Polar Orbitter (> 2011)
  - Europa/ Titan Orbiters/Explorers (>2016)
  - Inner Planetary Exploration Missions (>2014)
  - Human Lunar Surface Missions (> 2018)
- Future NASA missions require energy storage devices with mass and volume efficiency, long life capability and can operate safely in extreme environments

Adv. Energy Storage Technologies Under Development

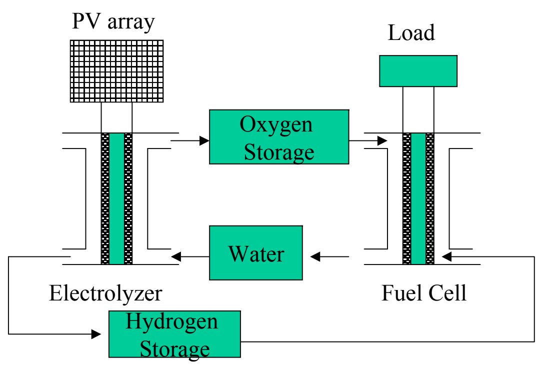




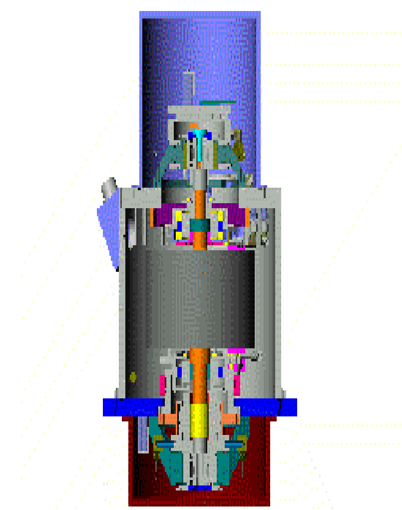
Li solid state Batteries



PEM Fuel Cells



Regenerative Fuel Cells



Flywheel System Schematic